Effect of Residual Noncondensables on Pressurization & Pressure Control of a Zero-Boil-Off Tank in Microgravity. M. Kassemi[1], S. Hylton[1], O. Kartuzova[1]. [1]National Center for Space Exploration (NCSER), NASA Glenn Research Center, Cleveland, OH 44135, USA.

The Zero-Boil-Off Tank (ZBOT) Experiment is a small-scale experiment that uses a transparent ventless Dewar and a transparent simulant phase-change fluid to study sealed tank pressurization and pressure control with applications to on-surface and in-orbit storage of propellant cryogens. The experiment will be carried out under microgravity conditions aboard the International Space Station in the 2014 timeframe. This paper presents preliminary results from ZBOT's ground-based research that focuses on the effects of residual noncondensable gases in the ullage on both pressurization and pressure reduction trends in the sealed Dewar. Tank pressurization is accomplished through heating of the test cell wall in the wetted and un-wetted regions simultaneously or separately. Pressure control is established through mixing and destratification of the bulk liquid using a temperature controlled forced jet flow with different degrees of liquid jet subcooling.

A Two-Dimensional axisymmetric two-phase CFD model for tank pressurization and pressure control is also presented. Numerical prediction of the model are compared to experimental 1g results to both validate the model and also indicate the effect of the noncondensable gas on evolution of pressure and temperature distributions in the ullage during pressurization and pressure control. Microgravity simulations case studies are also performed using the validated model to underscore and delineate the profound effect of the noncondensables on condensation rates and interfacial temperature distributions with serious implications for tank pressure control in reduced gravity.

*Project Supported by NASA ISS Physical Sciences Research Program, NASA HQ, USA.

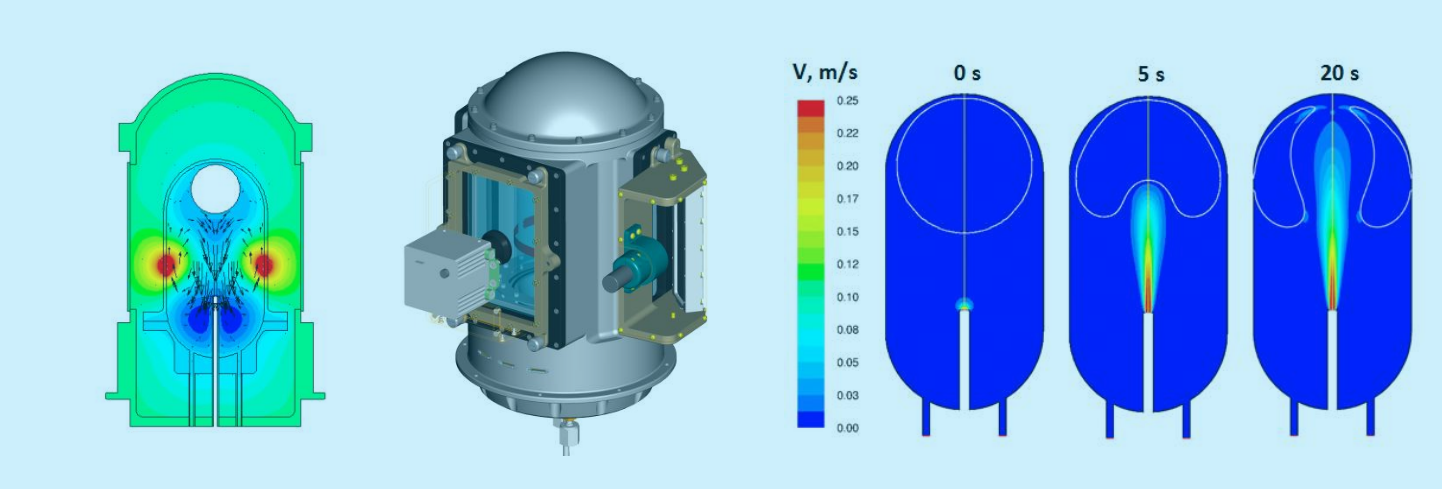
29th ASGSR Conference, Orlando, Florida

Effect of Residual Noncondensables on Pressurization & Pressure Control of a Zero-Boil-Off Tank in Microgravity

Mohammad Kassemi(CWRU/NCSER/GRC)

(Mohammad.Kassemi@nasa.gov)

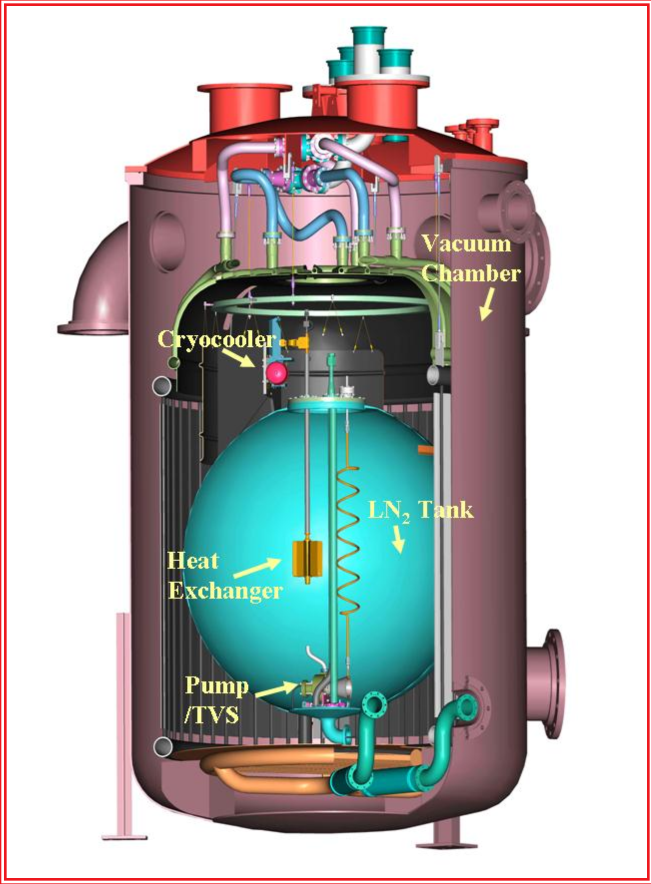
Sonya Hylton (NCSER/GRC), Olga Kartuzova (NCSER/GRC)



November 5, 2013

Background & Motivation

- Affordable and reliable in-orbit or on-surface cryogenic storage for propellant and/or life support consumables is essential to all stages of NASA's Exploration Program.
- Heat leaks from the surroundings can lead to liquid vaporization resulting in significant mass loss and/or significant increase in tank pressure.
- NASA has identified cryogenic storage & transfer as an area with greatest potential for cost saving
- Dynamic storage tank pressure control that involves some mode of mixing of the bulk liquid with or without active or passive cooling is needed to realize cost savings.
- To combat the unwanted effects of cryogen vaporization several strategies exist:
  - Venting ➔ Mixing/Venting➔ **Considerable mass Loss**
  - Venting ➔ Mixing/Passive Cooling (TVS)➔ **Reduced Mass Loss**
  - Ventless ➔ Active Cooling ➔ **ZBO**



Fundamental Multiphase Science Issues

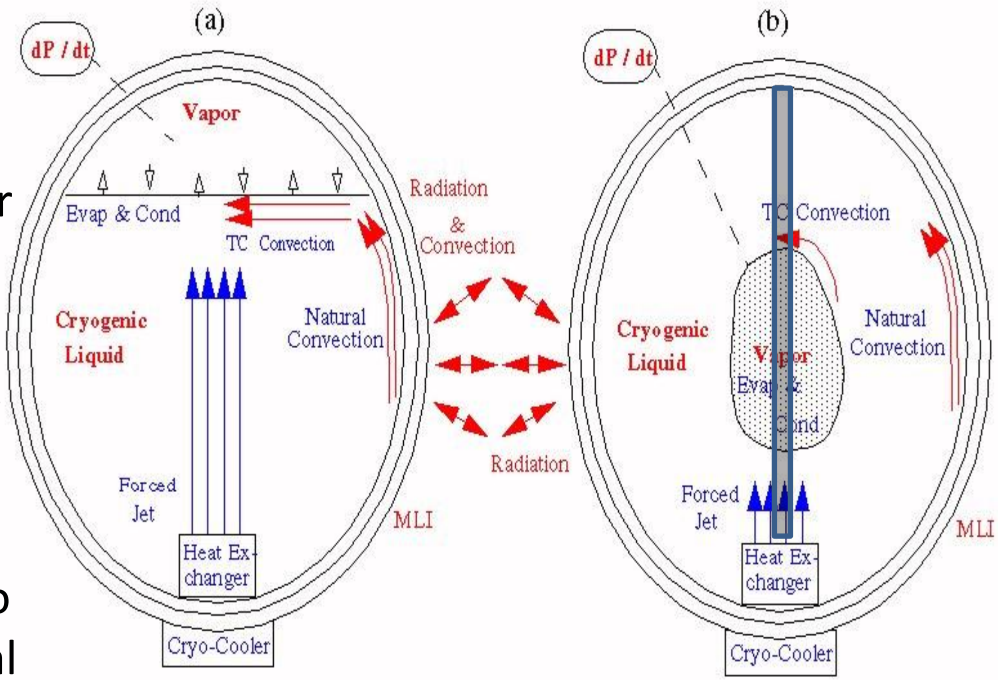
- Natural Convection
- Forced Mixing
- Evaporation Condensation
- Microgravity Superheats
- Non-Condensable Gases
- Transport Barrier
- Marangoni Convection
- Interfacial Kinetics
- Free Surface Dynamics
- Contact Angle Dynamics
- Sloshing/Droplet Transport
- Phase Control/Positioning

Due to unavailability of microgravity Data:

➢ Empirically-based engineering correlations for pressurization, mixing, destratification, pressure reduction, and fluid transfer time constants are scarce or based on ill-applied theory.

➢ Customized, and *fully*-validated CFD models are not available to aid the scale-up

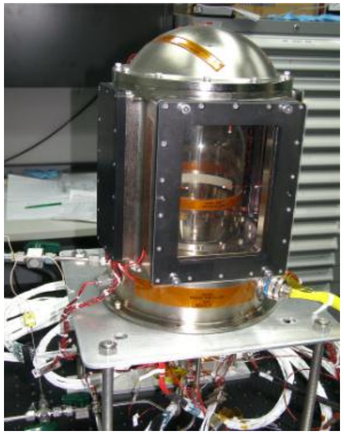
➢ Prediction of engineering models lack desired accuracy by a wide margin due to scarcity of microgravity relevant empirical correlations.

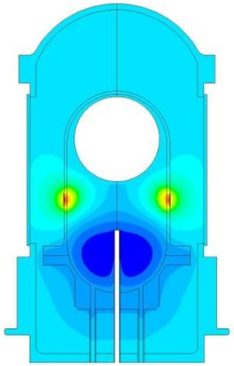


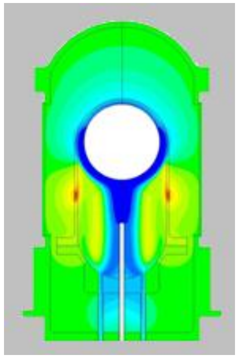
(3)

Zero-Boil-Off Tank (ZBOT) Experiment

- A small-scale *simulant*-fluid experimental platform to be accommodated in the Microgravity Science Glovebox (MSG) unit aboard the ISS.
- Obtain microgravity data for tank stratification, pressurization, mixing, destratification, and pressure control time constants during storage.
- Elucidate the roles of the various interacting transport and phase change phenomena that impact tank pressurization and pressure control in microgravity to form a scientific foundation for storage tank engineering.
- Develop a *state-of-the-art* CFD two-phase model for storage tank pressurization & pressure control.
- Validate and Verify the zonal- and CFD-based tank models using the microgravity data. Use the model and correlations to optimize and scale-up future storage tank design

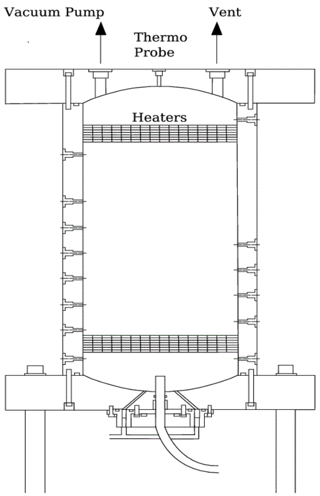


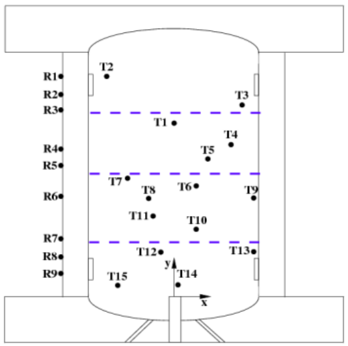


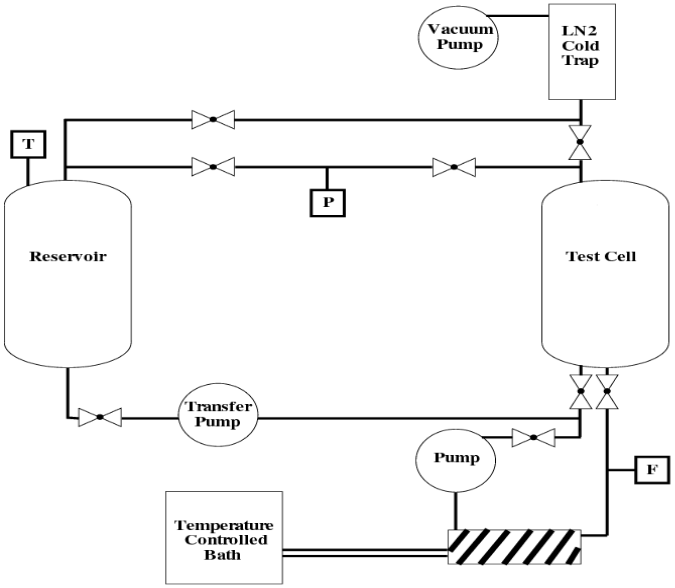


ZBOT: Small-Scale *Simulant* Fluid ISS Experiment
(Preliminary Ground-Based Tests)

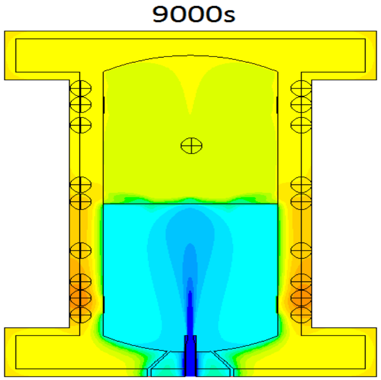
- Small Scale Experiment: 20 cm x 40 cm
- Simulant Fluid: HFE7000
- Transparent Dewar: Acrylic
- Liquid from a reservoir is degassed and pumped into the test cell.
- Pressurization is induced by Kapton strip heaters on the wetted and unwetted tank walls
- Pressure control is achieved through simultaneous mixing and cooling of the bulk liquid using a forced jet flow
- Temperature of the jet is maintained by a heat exchanger in the fluid support unit (FSU)
- Ullage Pressure measured by MKS Transducer
- Wall temperatures monitored with RTDs
- Ullage and liquid temperatures monitored by accurate thermistors (+/- 0.04 K)

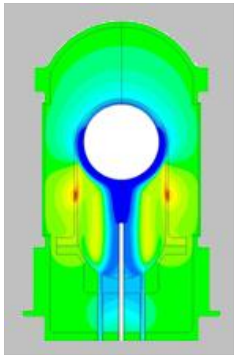






Two –Phase Storage Tank CFD Model





Equation	Liquid	Ullage
Continuity	√	√
Navier Stokes	√	√
Energy	√	√
Species		√
Turbulence (k-ω SST)	√	√

Interfacial Energy Balance:

$$LJ_v = -k_l \vec{\nabla} T_l \cdot \hat{n} + k \cdot \vec{\nabla} T \cdot \hat{n}$$ √

$$T_I = T_{sat}(P_v)$$ X

Schrage Interfacial Mass Transfer:

$$J_v = \frac{2\sigma}{2-\sigma}\frac{1}{\sqrt{2\pi R T_I}}[P_{sat}(T_I) - P_v]$$ √

$$\frac{P_{sat}(T_I)}{P_r} = e^{\left[\frac{L}{R}\left(\frac{1}{T_r}-\frac{1}{T_I}\right)\right]}$$ √

$$P_v = \frac{\omega_v M_g}{\omega_v M_g + (1-\omega_v) M_v} P$$ √

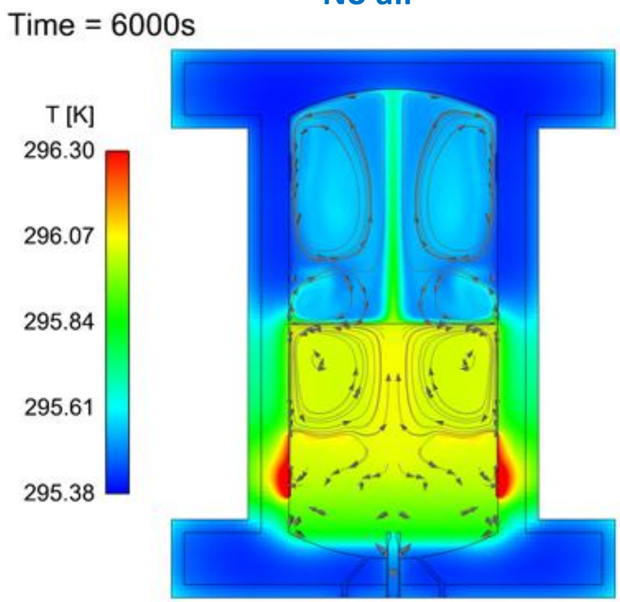
Stefan Wind:

$$J_v = -\left(\frac{\rho D_m}{1-\omega_v}\right)\nabla\omega \cdot \hat{n}$$ √

Effects of Residual Air (Non-Condensable) in the Ullage on Transport

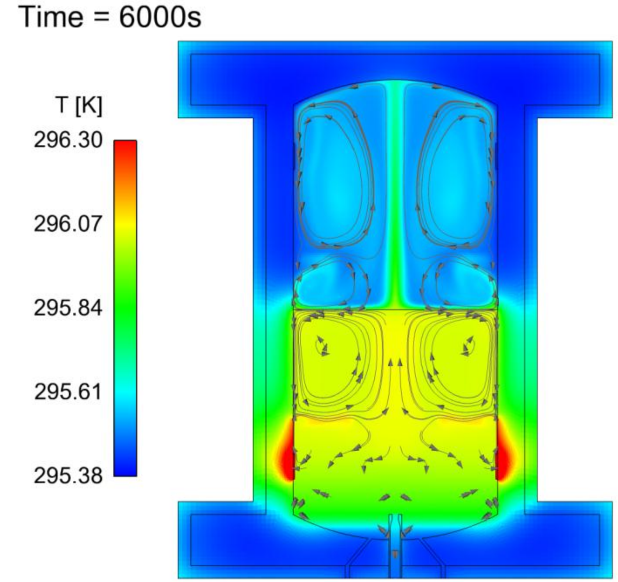
1G Self-Pressurization: *Model Prediction vs Experiment*

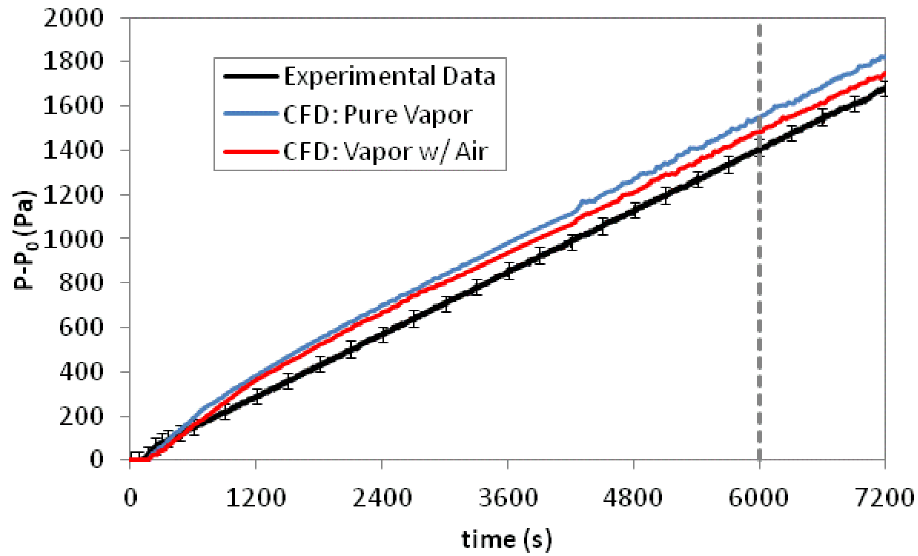
No air



Air at 20 Torr

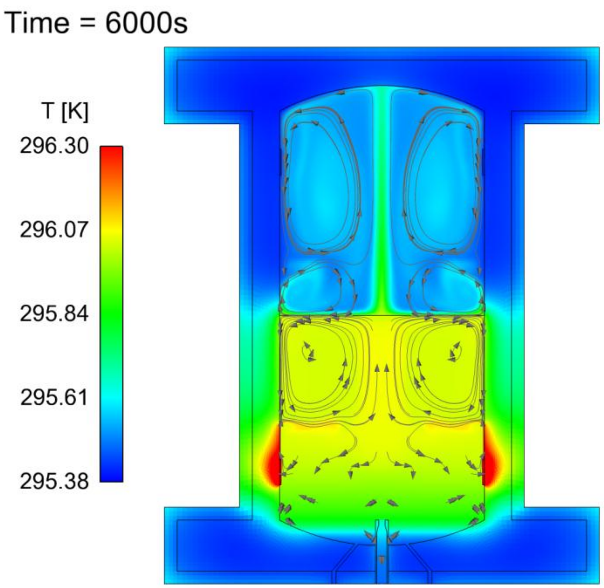
With Residual Air

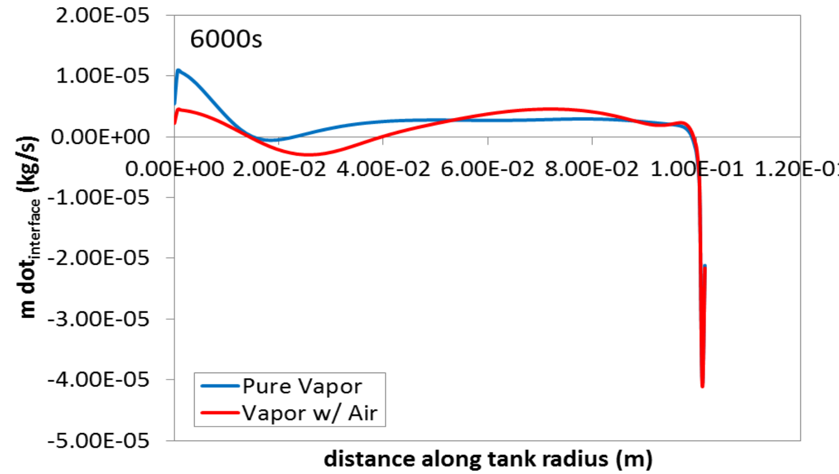


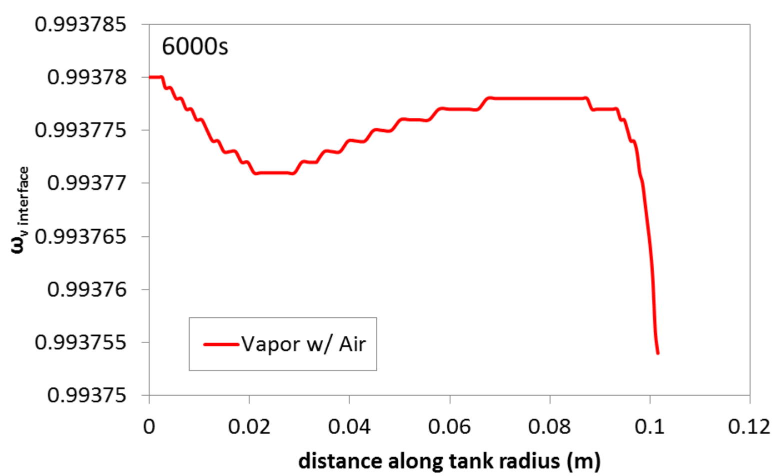


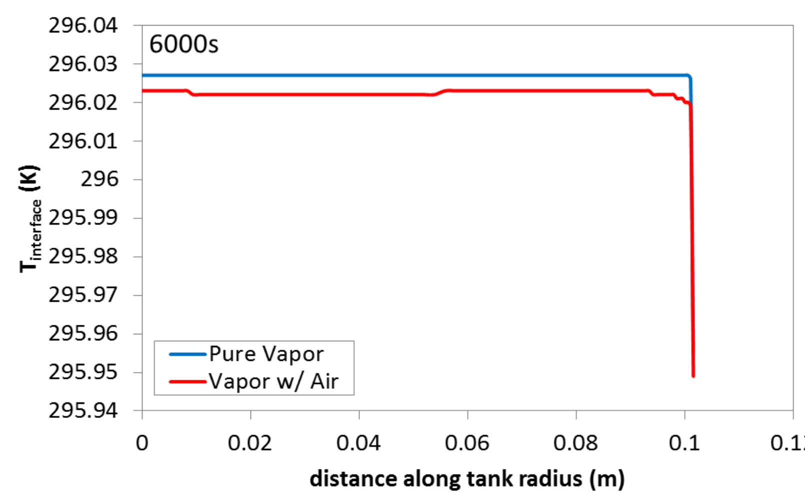
(8)

1G Self-Pressurization Simulations

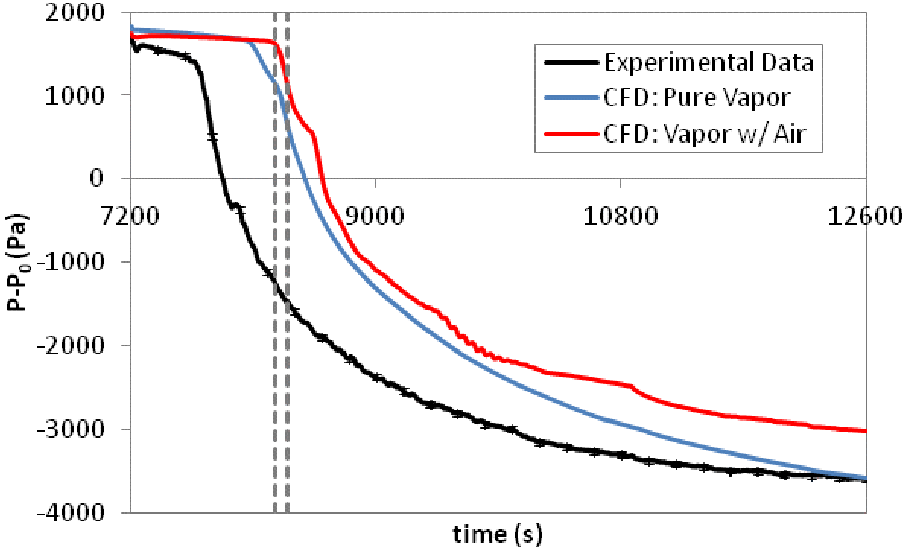


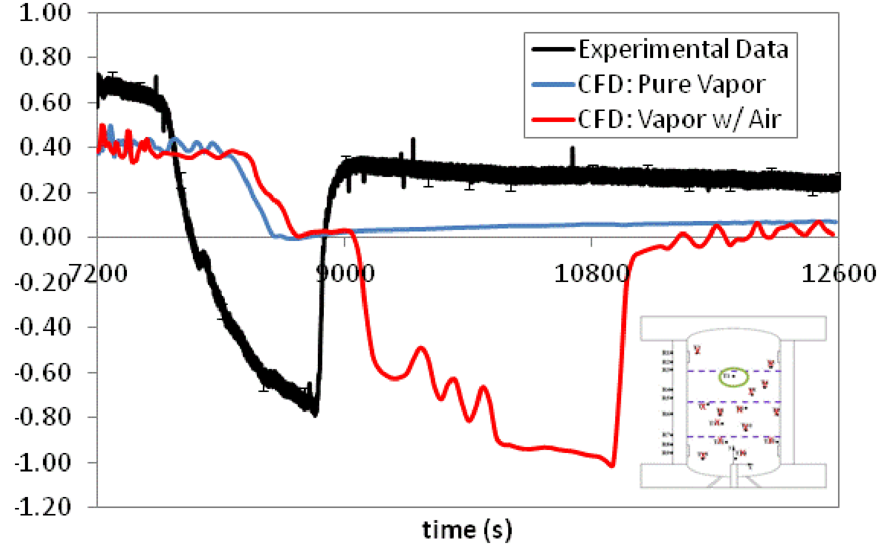




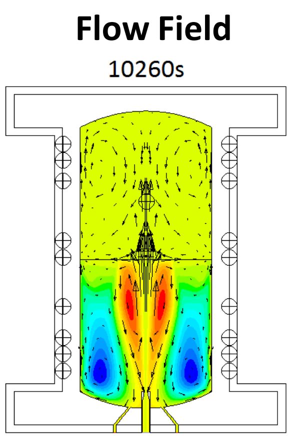


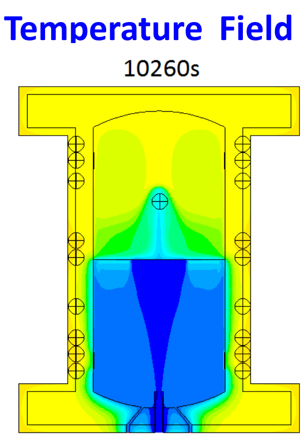
1G Pressure Control: *Model Prediction vs Experiment*





- Over-prediction of pressure drop lag.
- Good prediction of pressurization reduction rate.
- Good prediction of the main features of the non-intuitive temperature behavior/trend.
- Noticeable under-prediction of local ullage temperature.

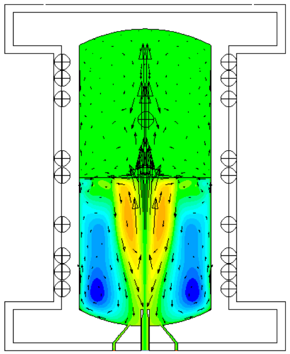




1G Pressure Control Simulations

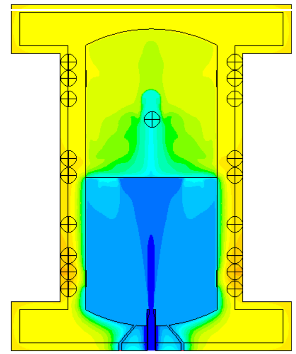
Flow Field

9720s



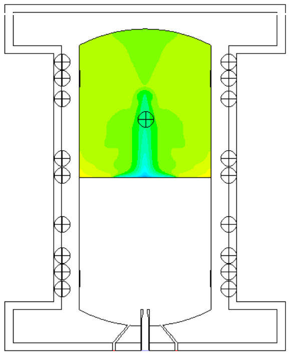
Temperature Field

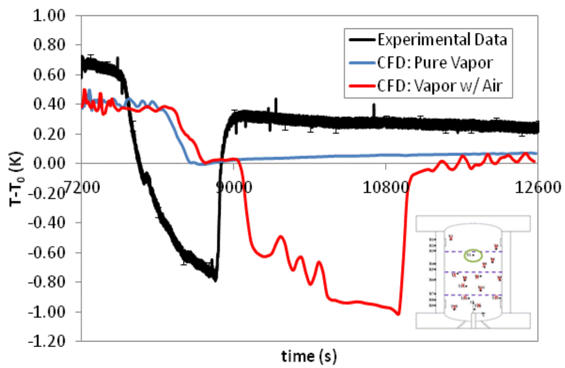
9720s



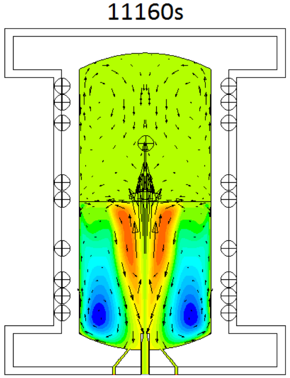
Concentration Field

9720s

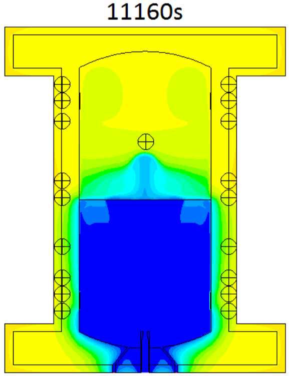




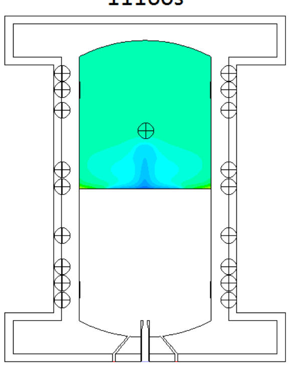
11160s



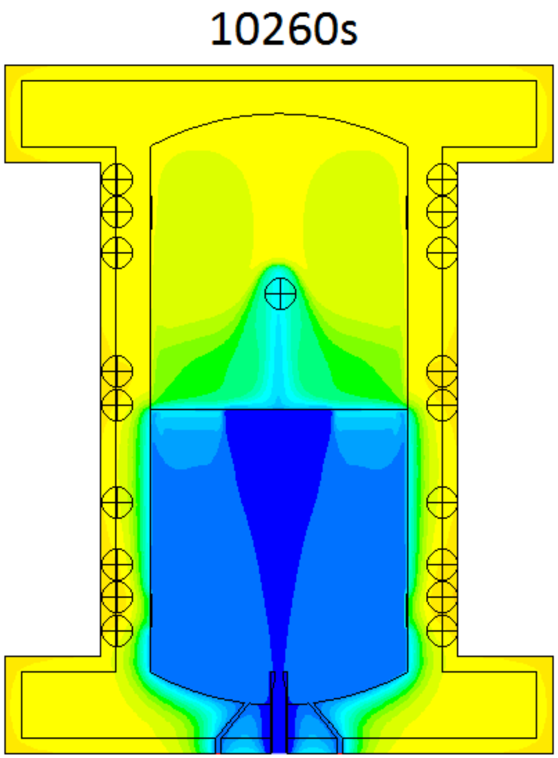
11160s

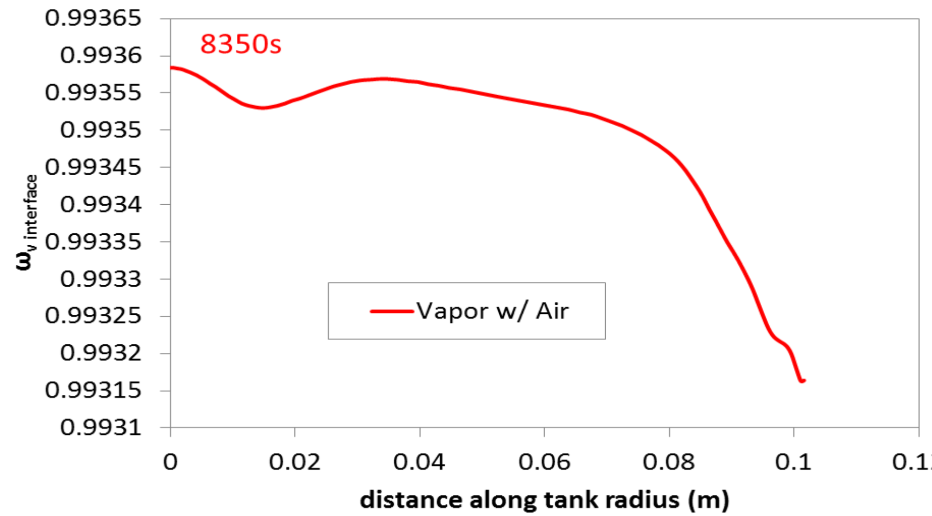


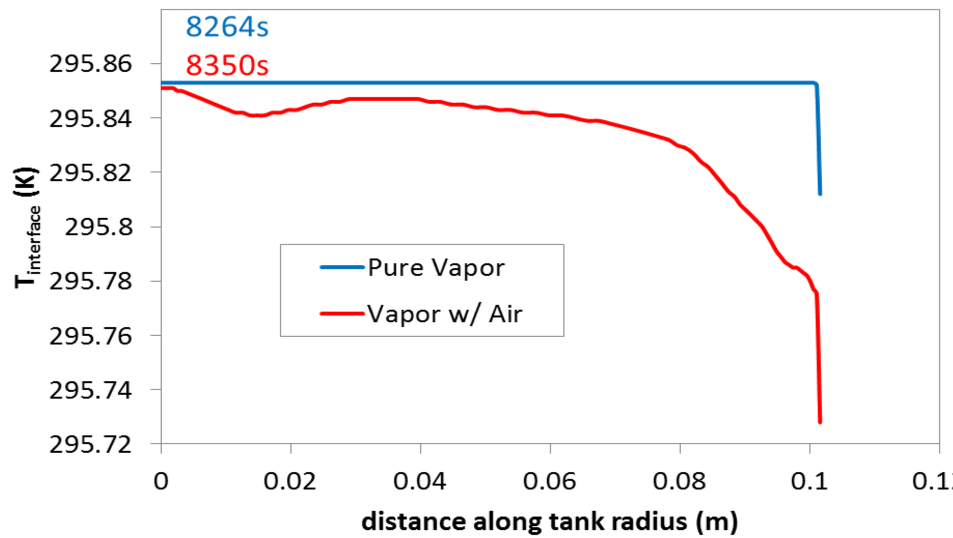
11160s



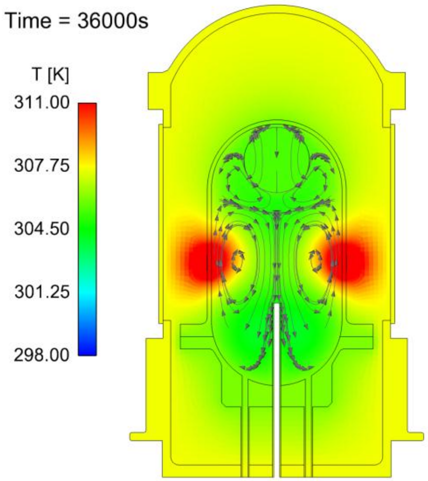
1G Pressure Control Simulations

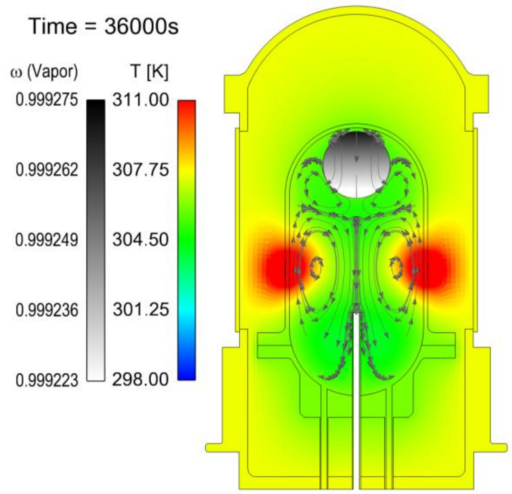


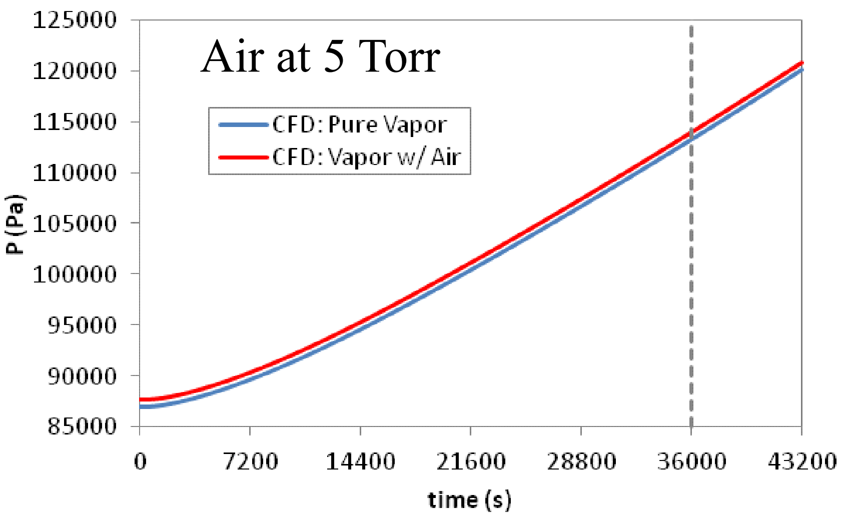




ZBOT Simulations- Microgravity Pressurization





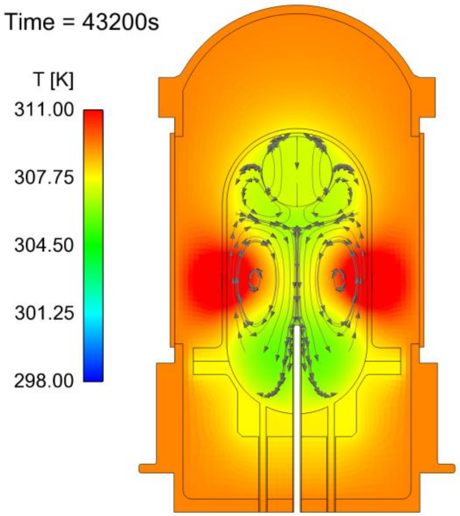


- Test Tank is enclosed in a vacuum jacket
- Tank is heated by a strip-heater placed circumferentially on the outside wall of the tank

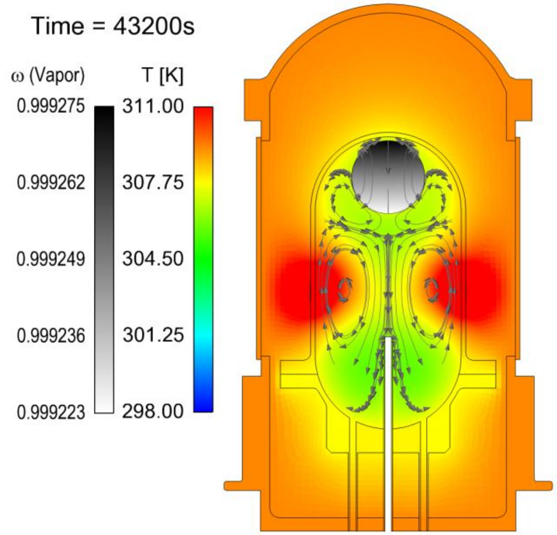
- In Microgravity, the ullage is spherical, the interface is curved *and* ***the tank wall is all wetted***.
- A prominent laminar natural convective torroidal flow ensues mainly near the heater and interface.
- The Microgravity thermal stratification pattern and its magnitude is significantly different from the 1G case.
- Ullage pressure still rises due to wall heating from the top.
- Flow becomes steady and stable.

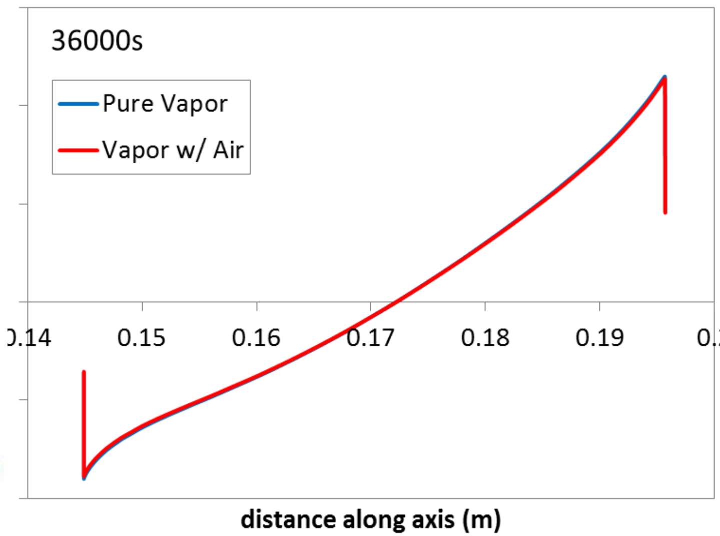
ZBOT Simulations- Microgravity Pressurization

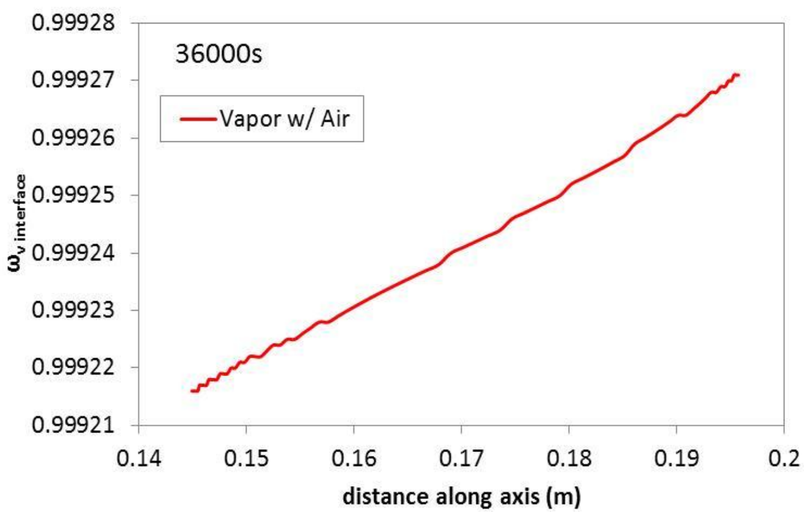
No air

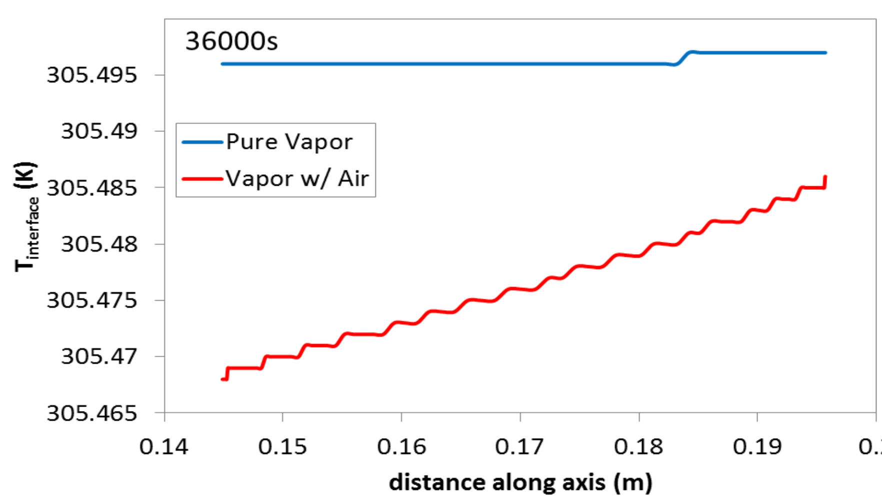


With Residual Air

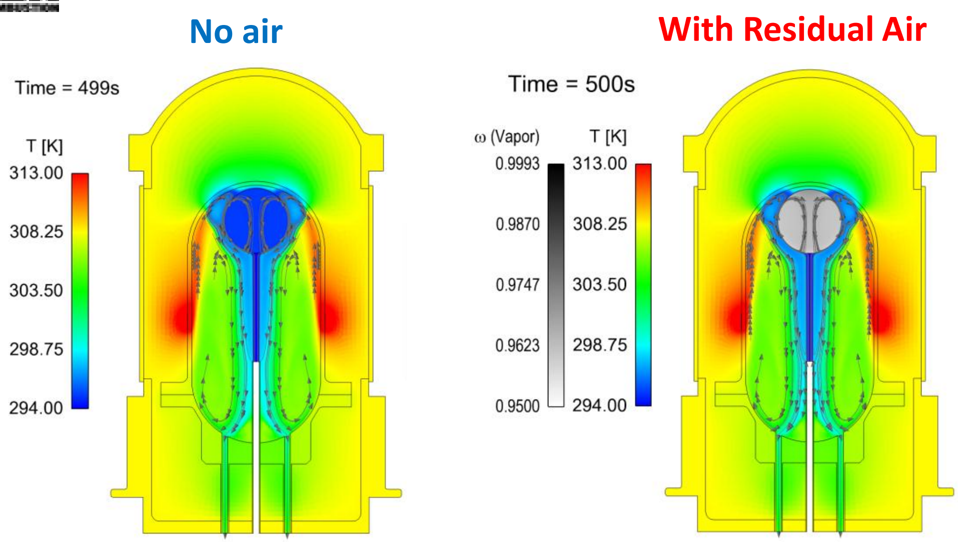


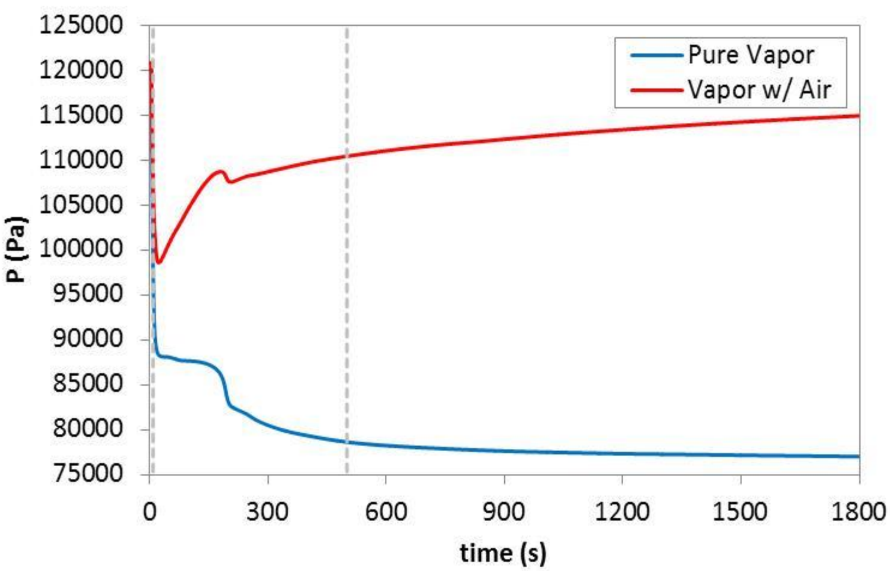






ZBOT Simulations: Micro-G Pressure Control





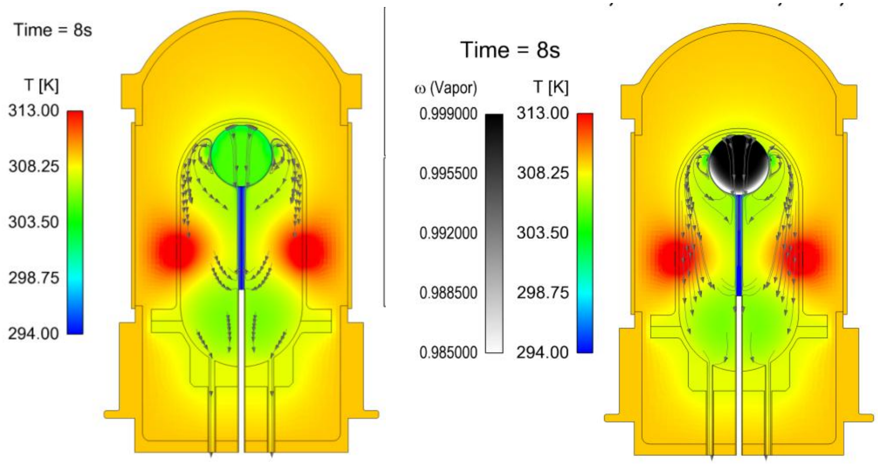
- In Micrograving, A forced sub-cooled jet is used to control the tank pressure.
- The sub-cooled jet flow impinges on the interface and *isolates* it from the heaters.
- Initially The test tank thermally de-stratifies rapidly using a 5 cm/s jet flow.
- The extent of pressure drop is however very sensitive to the residual air (noncondensable in the ullage)

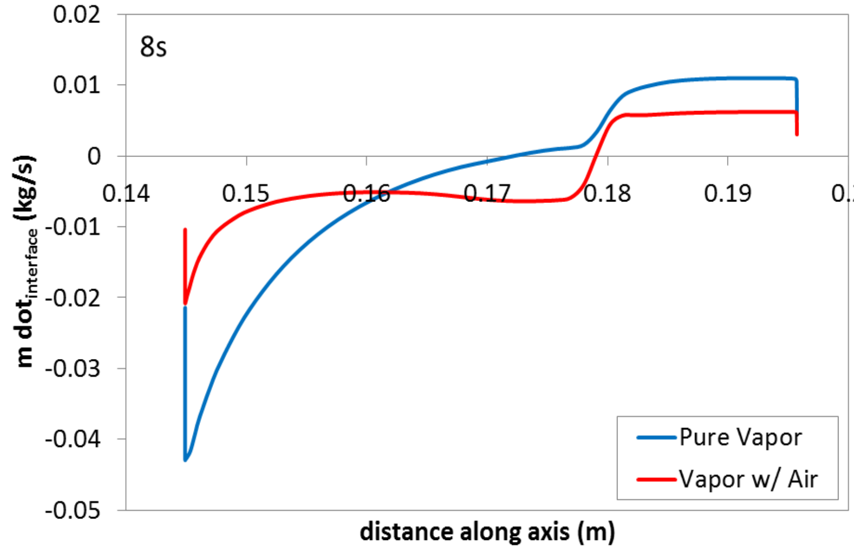
- Test Tank is enclosed in a vacuum jacket
- Tank is heated by a strip-heater placed circumferentially on the outside wall of the tank
- A forced sub-cooled jet is used for pressure control

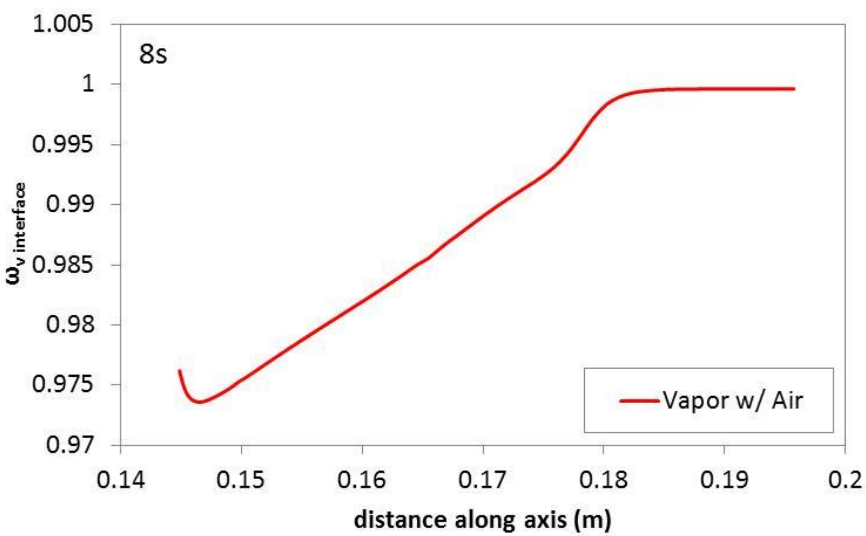
ZBOT Simulations: Micro-G Pressure Control

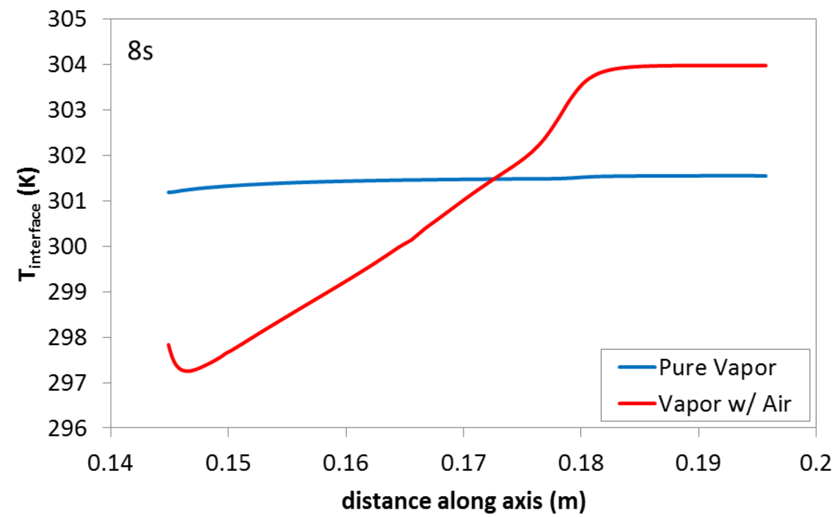
No air

With Residual Air



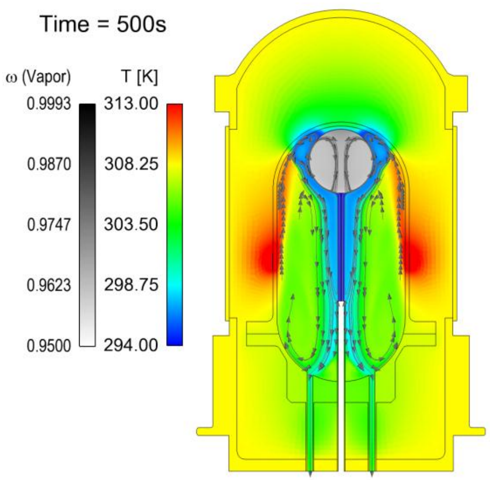




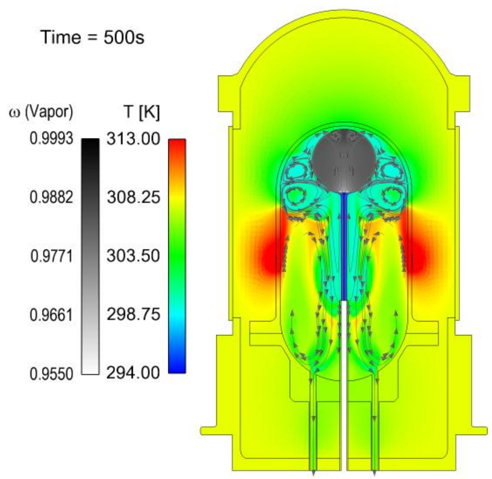


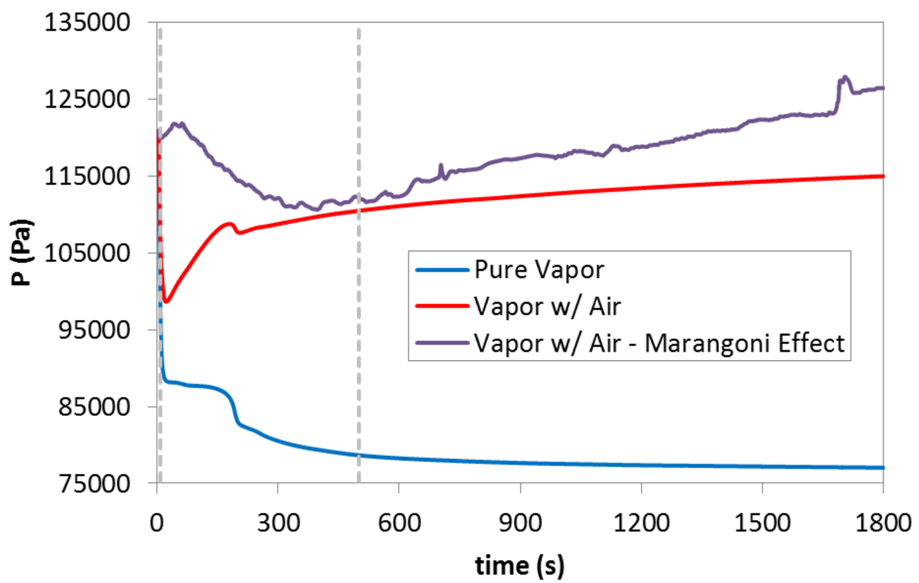
ZBOT Simulations: Micro-G Pressure Control

Residual Air



Residual Air-Marangoni

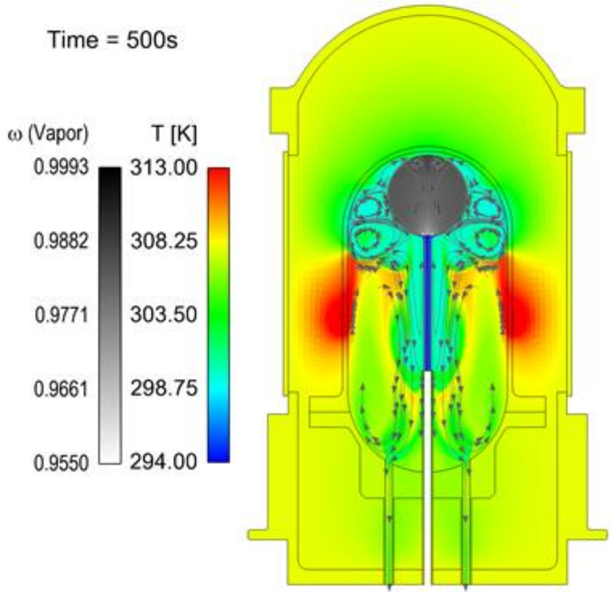


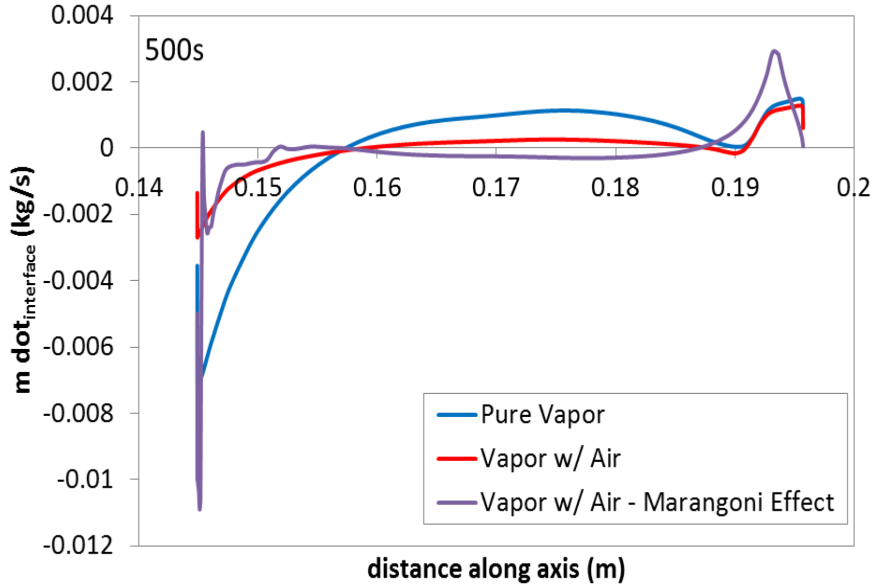


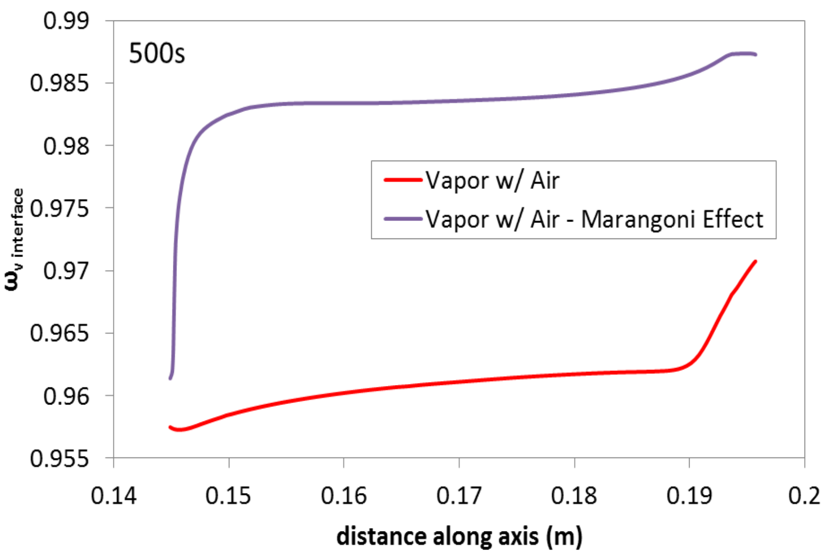
- In presence of residual non-condensable in Microgravity, a relatively strong Marangoni convection vortex restricts the spread of cooled-jet flow over the interface.
- Initial rate of pressure drop is significantly reduced
- Pressure in the tank eventually rises due to accumulation of non-condensable in the ullage impeding the transport of vapor to the interface

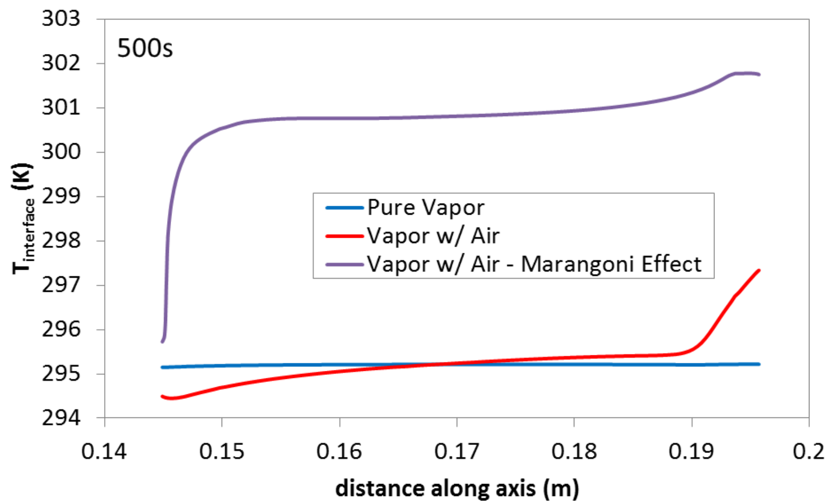
ZBOT Simulations: Micro-G Pressure Control

Residual Air-Marangoni

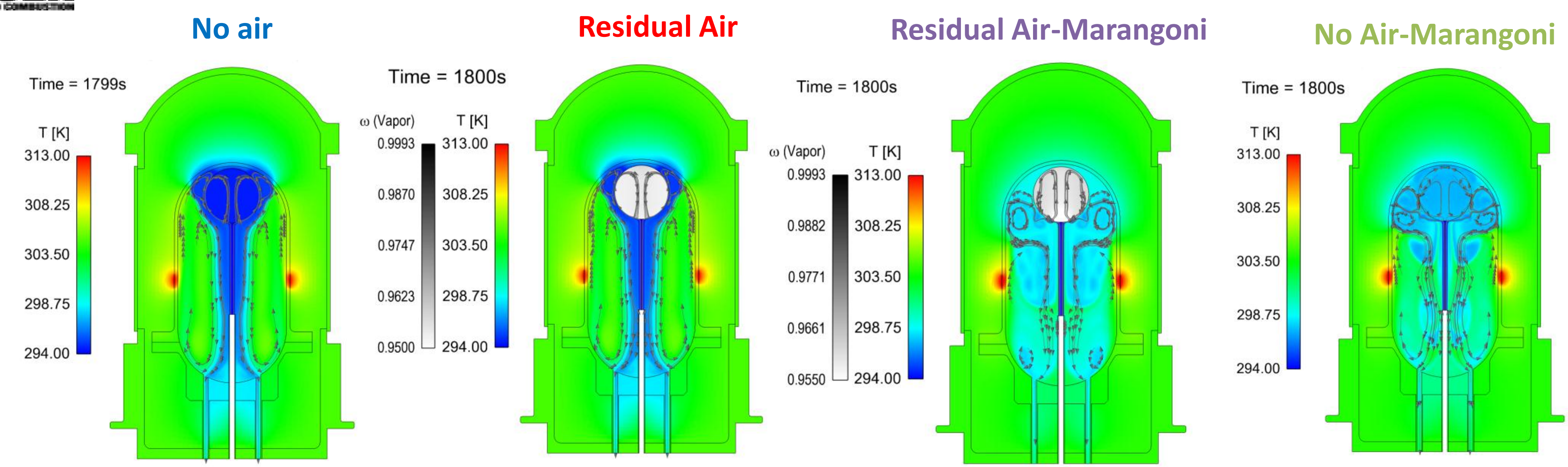


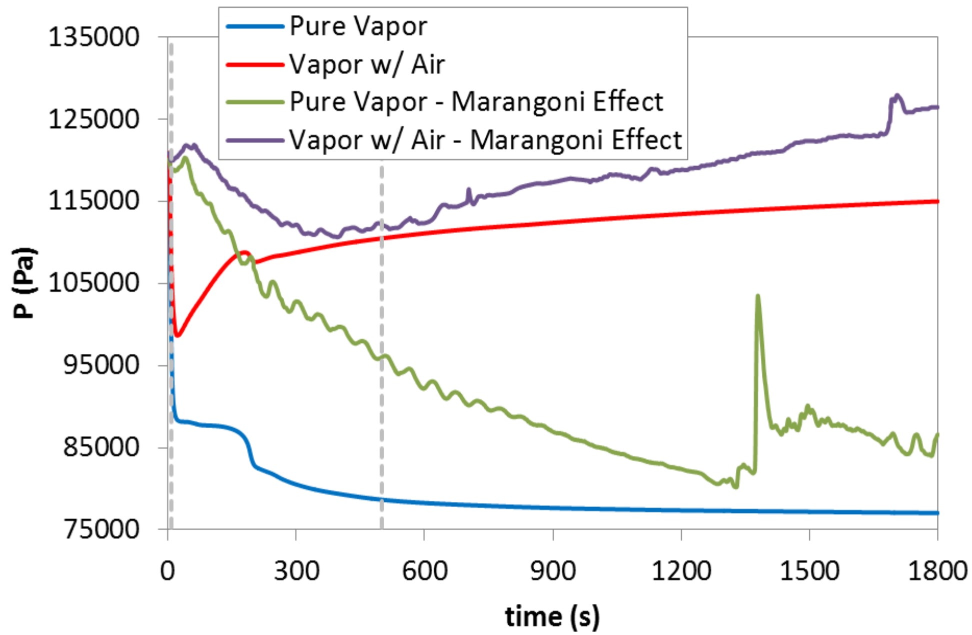






ZBOT Simulations: Micro-G Pressure Control



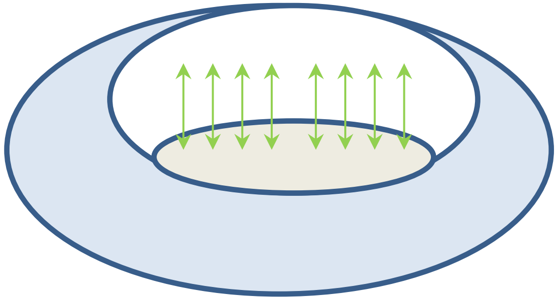


Closure: Noncondensable Gas Effects

❖ Transport in the Ullage:

Noncondensable impediment to vapor transport in ullage

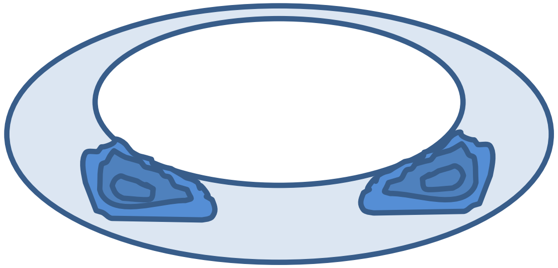
Panzarella & Kassemi (IJH&MT 2009)



❖ Fluid flow & mixing in the liquid:

Noncondensable instigates gravity-independent Marangoni mixing

(Straub-2001)



❖ Mass transfer kinetics at the interface:

Noncondensable forms kinetics barrier – **further mitigates condensation**

(Pong & Moses-1986)